DØ Note 6468-CONF

Inclusive production of the $X(4140)$ state in $p\overline{p}$ collisions at D0

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We present a first study of the inclusive production of the $X(4140)$ with the decay to $J/\psi\phi$ final state in hadronic collisions. We report the first evidence for the prompt production of $X(4140)$ and find the fraction of $X(4140)$ events originating from b hadrons to be $f_b = 0.39 \pm 0.07\,(\text{stat}) \pm 0.10\,(\text{syst})$. The ratio of the non-prompt $X(4140)$ production rate to the B_s^0 yield in the same channel is $R = 0.19 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$. New values of the mass $M = 4152.5 \pm 1.7(\text{stat})^{+4.7}_{-3.6}\,(\text{syst})$ MeV and width $\Gamma = 16.3 \pm 5.6\,(\text{stat}) \pm 10.3\,(\text{syst})$ MeV are consistent with previous measurements. The study is based on 10.4 fb^{-1} of $p\overline{p}$ collision data collected by the D0 experiment at the Fermilab Tevatron collider.

Preliminary Results for Summer 2015 Conferences

The $X(4140)$ state [1] was discovered in 2009 as a narrow structure in the $J/\psi\phi$ system near threshold. The CDF Collaboration reported the first evidence [2] for this state (termed $Y(4140)$) in the decay $B^+ \to J/\psi\phi K^+$ (charge conjugation is implied throughout) and measured the invariant mass $M = 4143.0 \pm 2.9(\text{stat}) \pm 1.2\,(\text{syst})$ MeV and width $\Gamma = 11.7^{+8.3}_{-5.0}\,(\text{stat}) \pm 3.7\,(\text{syst})$ MeV. The LHCb Collaboration found no evidence for the $X(4140)$ state [3] in a 2.4 standard deviation disagreement with the CDF measurement. However, the presence of $X(4140)$ in B^+ decay was later confirmed by the CMS [4] and D0 [5] Collaborations. Its quantum numbers have not been measured. Since both the J/ψ and ϕ mesons have $I^G J^{PC} = 0^- 1^{--}$, the $X(4140)$ state has positive G and C parities.

A meson with a charmed quark pair in the final state might be an excited charmonium state. However, the standard nonrelativistic quark model of a single $c\overline{c}$ pair does not predict a hadronic state at this mass. Also, at masses above the open-charm threshold of 3740 Me V such states are expected to decay predominantly to pairs of charmed mesons and to have a much larger width than experimentally observed. It has been suggested that $X(4140)$ could be a molecular structure made of two charmed mesons, e.g. $(D_s, \overline{D}_s)$. However, the Belle Collaboration found no evidence for $X(4140)$ in the process $\gamma\gamma \to J/\psi\phi$ [6], making its interpretation as a hadronic molecule with spin-parity $J^P = 0^+$ or 2^+ unlikely. Other possible states are hybrids composed of two quarks and a valence gluon ($q\overline{q}g$), four-quark combinations ($c\overline{c}s\overline{s}$), or states with higher Fock components [7]. For details see the review of hadronic spectroscopy in Ref. [8] and references therein.

In addition to $X(4140)$, the CDF Collaboration reported seeing a second enhancement in the same channel, located near 4280 MeV. A similar structure is seen by the CMS Collaboration [4]. Belle also reports a new structure at $M = 4350.6^{+4.6}_{-5.1}\,(\text{stat}) \pm 0.7\,(\text{syst})$ MeV.

In this Article we present results of a search for the $X(4140)$ resonance in the $J/\psi\phi$ system produced inclusively in $p\overline{p}$ collisions, either promptly, by pure QCD, or through weak decays of b hadrons. The measured production rates are normalized to the rate of the process $B^0_s \to J/\psi\phi$ measured with the same dataset. The data sample corresponds to an integrated luminosity of 10.4 fb^{-1} collected with the D0 detector in $p\overline{p}$ collisions at the Fermilab Tevatron collider.

The D0 detector consists of a central tracking system, calorimeters, and muon detectors [9]. The central tracking system comprises a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located inside a 1.9 T superconducting solenoidal magnet. The tracking system is designed to optimize tracking and vertexing for pseudorapidities $|\eta| < 3$, where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle with respect to the proton beam direction. The SMT can reconstruct the $p\overline{p}$ interaction vertex (primary vertex) for interactions with at least three tracks with a precision of 0.004 cm in the plane transverse to the beam direction. The muon detector, positioned outside the calorimeter, consists of a central muon system covering the pseudorapidity region $|\eta| < 1$ and a forward muon system covering the pseudorapidity region $1 < |\eta| < 2$. Both central and forward systems consist of a layer of drift tubes and scintillators inside 1.8 T iron toroidal magnets with two similar layers outside the toroids [10].

Events used in this analysis are collected with both single-muon and dimuon triggers. Muon triggers require a coincidence of signals in trigger elements inside and outside the toroidal magnets. Dimuon triggers in the central rapidity region require at least one muon to penetrate the toroid. In the forward region, both muons are required to penetrate the toroid. The minimum muon transverse momentum is 1.5 GeV.

We study a wide range of the $J/\psi\phi$ invariant mass, from threshold to 5.7 GeV, covering both the $X(4140)$ and the decay $B^0_s \to J/\psi\phi$. Candidate events are required to include a pair of oppositely charged muons in the invariant mass range $2.9 < M(\mu^+\mu^-) < 3.3$ GeV, consistent with J/ψ decay, accompanied by two additional particles of opposite charge, assumed to be kaons, with $p_T > 0.4$ GeV and $1.011 < M(K^+K^-) < 1.030$ GeV. In the event selection, both muons are required to be detected in the muon chambers inside the toroidal magnet, and at least one of the muons is required to be also detected outside the iron toroid [10]. Each muon candidate is required to match a track found in the central tracking system, and each of the four final-state tracks is required to have at least one SMT hit and at least one CFT hit. The dimuon invariant mass is constrained to the world-average J/ψ mass [1], and the four-track system is constrained to a common vertex. To reconstruct the primary vertex, tracks are selected that do not originate from the $J/\psi\phi$ candidate, and a constraint is applied to the average beam position in the transverse plane. We define the signed decay length of the $J/\psi\phi$ system, L_{xy}, to be the vector pointing from the primary vertex to the decay vertex, projected onto the direction of the transverse momentum. The distribution of L_{xy} for events within the ϕ signal window is shown in Fig. 1. We require $J/\psi\phi$ candidates to have $5 < p_T < 20$ GeV and rapidity $|y| < 2$.

We focus on two ranges of the $J/\psi\phi$ invariant mass, $M(J/\psi\phi) < 4.36$ GeV and $4.8 < M(J/\psi\phi) < 5.7$ GeV. The low-mass range includes the $X(4140)$ state. The high-mass range includes the reference decay process, $B^0_s \to J/\psi\phi$. Background arises primarily from non-resonant pairs in the ϕ mass window. At low L_{xy}, background comes from J/ψ mesons directly produced in $p\overline{p}$ collisions combined with random particles from the underlying event. At higher values of L_{xy}, background consists of J/ψ mesons paired with random products of b hadron decays.

We divide each sample into three independent subsamples according to the value of L_{xy}: (1) $-0.025 \le L_{xy} < 0$ cm, (2) $0 \le L_{xy} \le 0.025$ cm, and (3) $L_{xy} > 0.025$ cm. Region 1 includes half of the prompt events and almost no B-decay events. Region 2 includes the remaining half of all prompt events and a fraction of non-prompt events. The rest of the non-prompt events populate region (3). Given the average resolution of 0.006 cm in L_{xy}, we assume that the

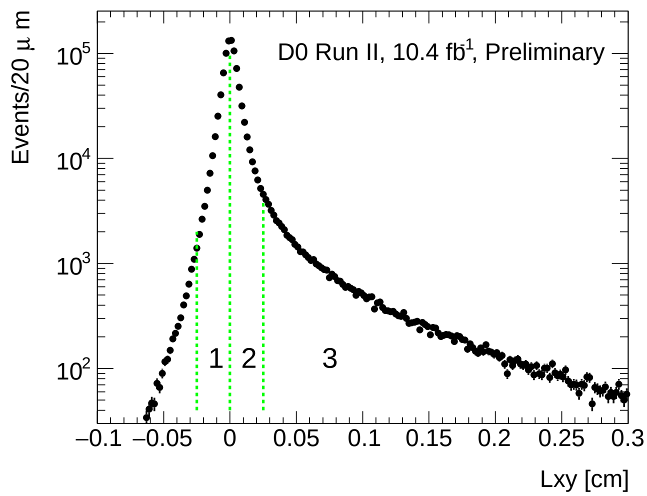

FIG. 1: Top: Decay-length distribution of $J/\psi\phi$ candidates. The vertical lines define the three regions discussed in the text.

fraction of prompt events in Region 3 is negligible. We perform binned maximum likelihood fits to the distributions of the $J/\psi\phi$ invariant mass for events in the six subsamples defined above. In the fits in the B_s^0 mass region, the signal is described by a Gaussian function and background is described by a second-order Chebychev polynomial. We also allow for the presence of the decay $B^0 \to J/\psi\phi$, where we set the mass to the world-average B^0 mass, and we find no evidence of a signal. The fit for Region 3 yields 3166 ± 81 B_s^0 events, with a width of 26.5 MeV and a mass that is lower than the world-average value by 4.6 ± 0.7 MeV.

In fitting the low mass range, we assume a signal described by an $\mathcal{S}$-wave relativistic Breit-Wigner function convolved with a Gaussian resolution of $\sigma(M) = 4$ MeV. Background is parametrized by the function $f(m) \propto m \cdot (m^2/m_{\rm thr}^2 - 1)^{c_1} \cdot e^{-m \cdot c_2}$ where $m_{\rm thr}$ is the kinematic threshold, and c_1 and c_2 are free parameters. For events in the L_{xy} Region 3, we allow the signal mass and width parameters to vary. The fit yields 616 ± 170 signal events, a mass of 4152.5 ± 1.7 MeV, and a width of 16.3 ± 5.6 MeV. The statistical significance of the signal, based on the increase of the likelihood with respect to the fit with no signal, $-2\Delta \ln \mathcal{L} = 42.5$ for 3 degrees of freedom, is 5.9 standard deviations. For the fits in L_{xy} Regions 1 and 2 we set the mass and width to the Region 3 values.

The mass distributions with superimposed fits for both mass regions and for all three L_{xy} are shown in Fig. 2. The $X(4140)$ and B_s^0 yields are presented in Table I. We also show the expected number of $X(4140)$ events originating from b-hadron decays in the two low L_{xy} regions assuming that the L_{xy} distribution of "non-prompt" $X(4140)$ is similar to that of B_s^0. For the ranges 1 and 2, we find an excess of signal events, indicating prompt production of $X(4140)$. For events in Region 2, the increase in the likelihood between the fit with a free signal yield and the fit with the expected non-prompt contribution only, $-2\Delta \ln \mathcal{L} = 23.6$, corresponds to a statistical significance of 4.9σ for the net prompt signal. The statistical significance of the total signal in this L_{xy} region is 6.2σ. For Region 1, the corresponding values of statistical significance are 3.9σ and 4.2σ. If the mass and width parameters are allowed to vary, the fit for Region 2 gives the total yield $N = 932 \pm 216$, $M = 4146.8 \pm 2.4$ MeV, and $\Gamma = 15.8 \pm 3.8$ MeV. The data in Region 1 do not yield a stable fit. Fixing the $X(4140)$ mass to 4152.5 MeV in this region we fit a total yield of $N = 601 \pm 205$ and Γ of 19.8 ± 5.9 MeV.

TABLE I: Summary of event yields in three L_{xy} regions and their sum for B_s^0 and $X(4140)$. For Regions 1 and 2 the mass of $X(4140)$ is assumed to be 4152.5 MeV. Also shown are the deduced yields for the non-prompt and prompt production of $X(4140)$. The uncertainties are statistical.

Parent	$-0.025 < L_{xy} < 0$ cm	$0 < L_{xy} < 0.025$ cm	$L_{xy} > 0.025$ cm	Sum
B_s^0	191 ± 143	804 ± 169	3166 ± 81	4161 ± 236
$X(4140)$	511 ± 120	837 ± 135	616 ± 170	1964 ± 248
$X(4140)$ non-prompt	37 ± 26	156 ± 31	616 ± 170	809 ± 175
$X(4140)$ prompt	474 ± 123	681 ± 139	$\equiv 0$	1155 ± 186

There are several uncertainties that may affect measurements of the $X(4140)$ yield, mass, and width, the ratio R of the yields of non-prompt $X(4140)$ and B_s^0, and the fraction f_b of all $X(4140)$ events that originate from weak decays of b hadrons.

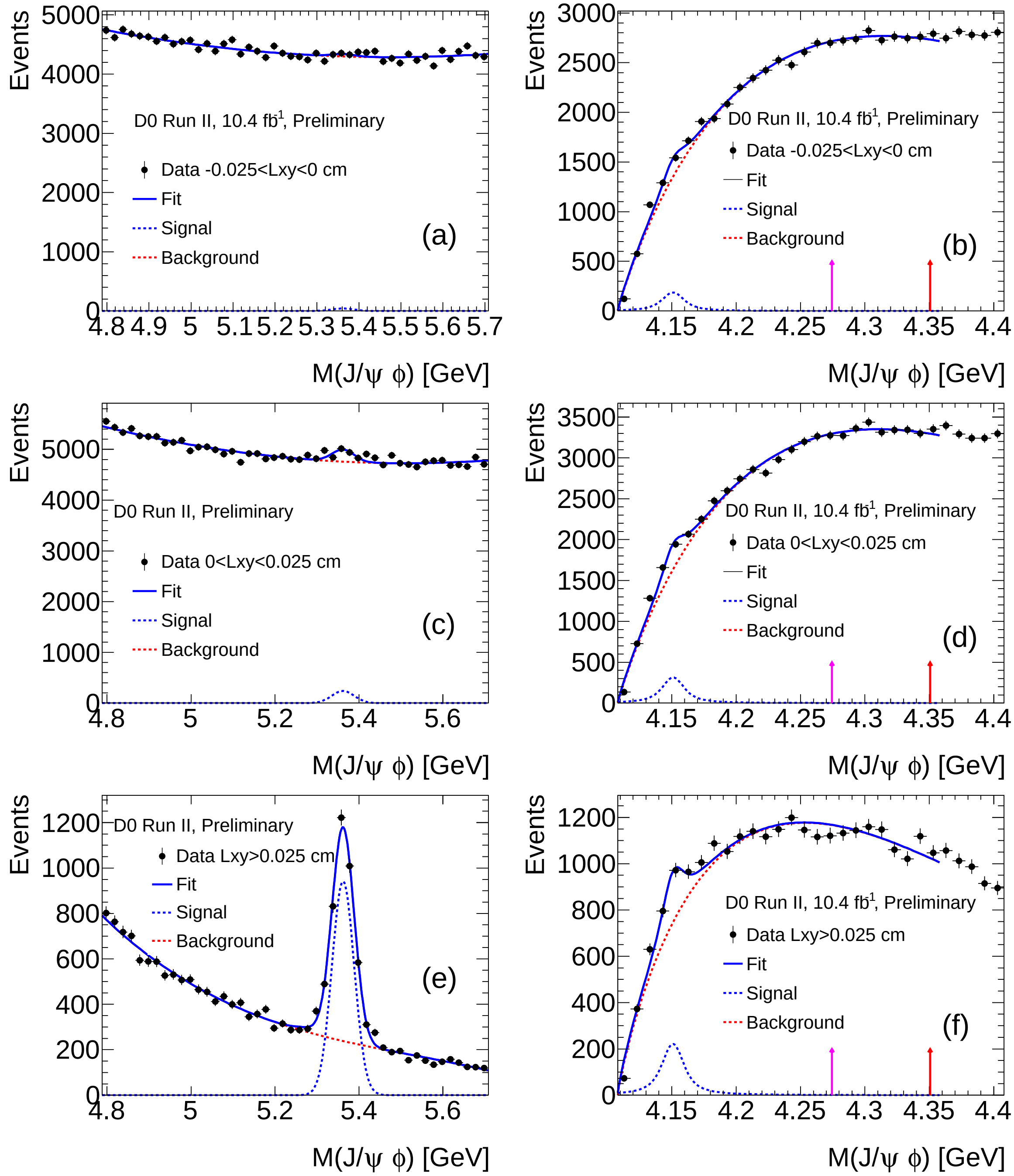

FIG. 2: (color online) Invariant mass distribution of $J/\psi\phi$ candidates in the mass window around (left) B_s^0 and (right) $X(4140)$, for events with (a,b) $-0.025 < L_{xy} < 0$ cm, (c,d) $0 < L_{xy} < 0.025$ cm and (e,f) $L_{xy} > 0.025$ cm. The arrows indcate the structures seen by CDF [2] and Belle [6]. The signal and background models are described in the text.

The mass resolution of 4.0 ± 0.1 MeV, obtained in simulations, is in agreement with an approximately linear rise with the released kinetic energy for decays with a similar topology: $\psi(2S) \to J/\psi\pi^+\pi^-$, $X(3872) \to J/\psi\pi^+\pi^-$, and the decay $B_s^0 \to J/\psi\phi$ mentioned above. We assign an uncertainty of ± 0.1 MeV to the resolution at the $X(4140)$ mass.

We assign an asymmetric uncertainty of 3 MeV to the $J/\psi\phi$ mass scale in the vicinity of $X(4140)$, based on the mass deficit of 2.7 ± 0.3 MeV found for $\psi(2S)$ and the B_s^0 mass bias. We assign the uncertainty in the signal model, taken from the range of results obtained with relativistic and nonrelativistic Breit-Wigner shapes and a relativistic P-wave Breit-Wigner shape. Simulations show the event reconstruction and selection efficiency to be indpendent of the

TABLE II: Summary of systematic uncertainties.

Source	Mass (MeV)	Width (MeV)	Rate non-prompt (%)	Rate prompt (%)
Mass resolution	± 0.1	± 0.2	± 1	± 1
Mass bias	${}^{+3}_{-0}$	–	–	–
Signal model	± 1	± 2.7	± 13	± 15
Fitting range	± 3	± 7.0	± 20	± 6
Bin size	± 1.6	± 7.0	± 25	± 10
Trigger bias	–	–	–	5
Mean lifetime	–	–	-1.5	$+1.5$
Total	${}^{+4.7}_{-3.6}$	± 10.3	± 35	± 19

$M(J/\psi\phi)$ invariant mass, with a possible bin-to-bin variation of $\pm 10\%$. The possible variation of the efficiency within the $X(4140)$ mass range affects the mass, width, and yield of the signal. To assess effects of the fitting procedure and background size and shape, we vary the fitting mass range and bin size. Some of the single-muon triggers include a filter requiring a presence of tracks with non-zero impact parameter. Events recorded by such triggers constitute approximately 5% of all events. Assuming that such triggers are 100% efficient for b events and reject all prompt events, we apply a 5% correction to the prompt yield. We assign a systematic uncertainty of $\pm 5\%$ on the fraction f_b due to this correction. Finally, our assumption of the equality of the relative rates in regions (1) − (3) for the non-prompt $X(4140)$ and B^0_s is based on expectation of the equality of the average lifetime of b-hadron parents of the $X(4140)$ and that of the B^0_s in the $J/\psi\phi$ channel. The world-average of the B^0_s lifetime is 6% lower than the lifetime averaged over all b hadron species [1]. We assign an asymmetric uncertainty in the ratio R and the fraction f_b. The systematic uncertainties are summarized in Table II.

We test the stability of the results to the event selection by changing the ϕ mass window to $1.012 < M(K^+K^-) < 1.029$ GeV. As additional cross-checks, we perform fits to subsamples corresponding to the transverse momentum ranges $5 < p_T < 10$ GeV and $10 < p_T < 20$ GeV; to early and late data-taking periods; and to events in the central and forward rapidity regions. In each case, the background shape in the two subsamples is well described by the same functional form although it requires different values of the parameters. In all cases the sums of the resulting signal yields agree with the total yield within a few events.

Our measured values of the mass and width of the $X(4140)$ state are compared with earlier measurements in Table III. The ratio of the $X(4140)$ to B^0_s yield for events with $L_{xy} > 0.025$ cm is $R = 0.19 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$. After correcting for the efficiency of this L_{xy} cut and for the trigger bias, we find the fraction of $X(4140)$ events originating from b hadrons to be $f_b = 0.39 \pm 0.07\,(\text{stat}) \pm 0.10\,(\text{syst})$. The yield for the $X(4140)$ state at $L_{xy} > 0.025$ cm can also be compared with the yield of 52 ± 19 events of $X(4140)$ from the decay process $B^+ \to J/\psi\phi K^+$ obtained by D0 [5] for the same data set. After correcting for a factor of 2.5 ± 0.5 for the efficiency of the full reconstruction of the B^+ decay and lower kaon p_T threshold, we expect the yield from the B^+ decay to be $\approx 130 \pm 60$ events in this analysis. Our observed yield of 616 ± 170 events exceeds this estimate suggesting that decays of b hadrons other than B^+ contribute to the non-prompt production of $X(4140)$. The $J/\psi\phi$ invariant mass distributions presented in Fig. 2 show no evidence for states in the mass region $4250 < M(J/\psi\phi) < 4375$ MeV.

TABLE III: Summary of $X(4140)$ measurements

Experiment	Process	Mass (MeV)	Width (MeV)
CDF [2]	$B^+ \to J/\psi\phi K^+$	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$
CMS [4]	$B^+ \to J/\psi\phi K^+$	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$
D0 [5]	$B^+ \to J/\psi\phi K^+$	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+3.0}_{-8.0}$
D0 (this work)	$\overline{p}p \to J/\psi\phi + \text{anything}$	$4152.5 \pm 1.7^{+4.7}_{-3.6}$	$16.3 \pm 5.6 \pm 10.3$

In summary, we have carried out the first search for inclusive production of the state $X(4140)$ in hadronic collisions. We find evidence for its direct, prompt production, and observe a production in weak decays of b hadrons with a rate exceeding the expected rate for the known decay $B^+ \to J/\psi\phi K^+$. The significance of the prompt production, including systematic uncertainties, is 4.7σ. This is the first evidence for the prompt production of $X(4140)$. The significance of the non-prompt production, including systematic uncertainties, is 5.6σ. The non-prompt production rate of $X(4140)$ relative to B^0_s observed in the same final state is $R = 0.19 \pm 0.05\,(\text{stat}) \pm 0.07\,(\text{syst})$. We see the need for more b-hadron states to feed the non-prompt signal than just the previously known B^+ decays. Assuming a relativistic Breit-Wigner line shape, we measure the mass and width of the $X(4140)$ state to be $M = 4152.5 \pm 1.7(\text{stat})^{+4.7}_{-3.6}\,(\text{syst})$ MeV and width $\Gamma = 16.3 \pm 5.6\,(\text{stat}) \pm 10.3\,(\text{syst})$ MeV, consistent with previous measurements [2, 4, 5].

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